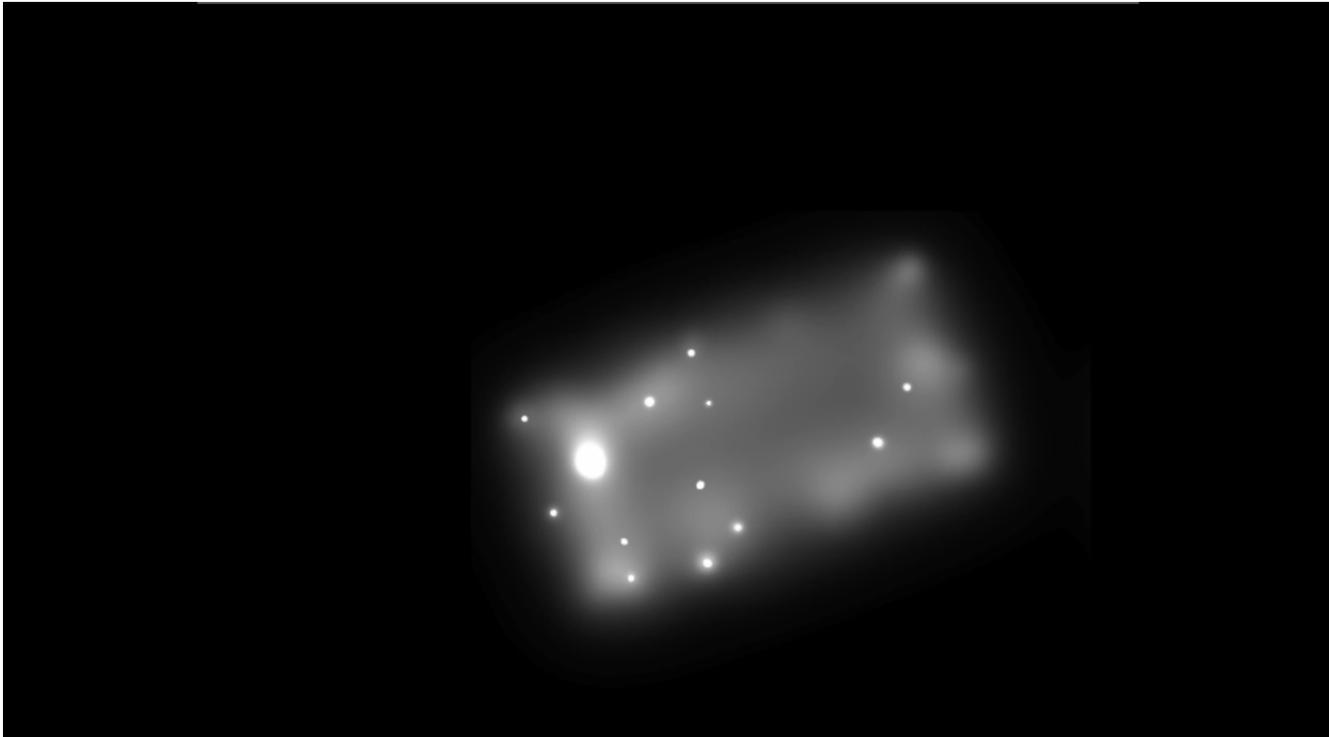


# Populations of High Mass X-ray Binaries

Silas Laycock

UMass Lowell, Center for Space Science & Technology

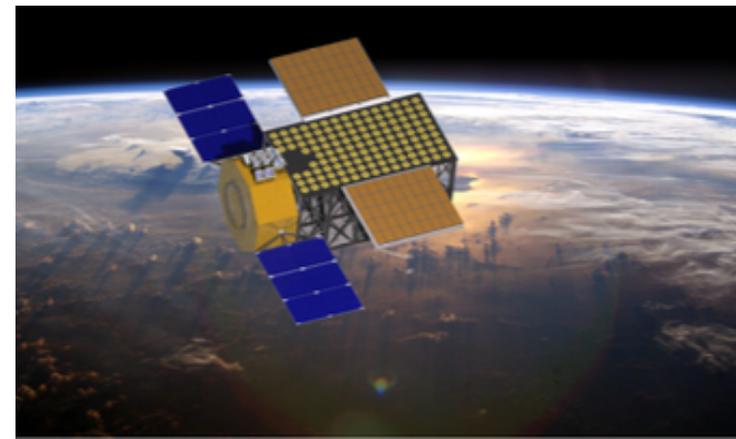




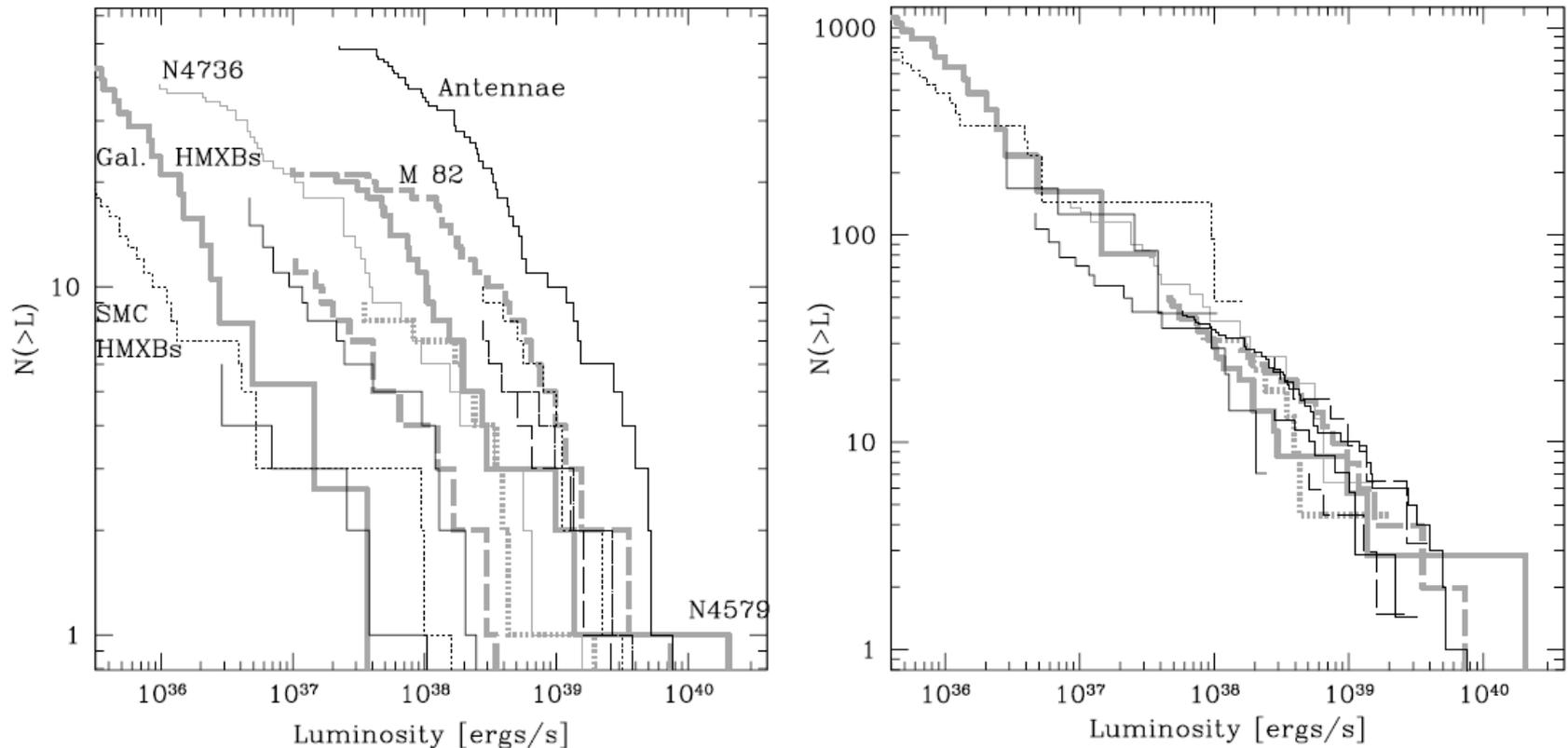
# STROBE-X and HMXBs



- **End the photon-starvation bottleneck that we have reached**
  - Chandra and XMM have revolutionized the study of XRB populations by isolating and identifying individual sources within many hundreds of galaxies
  - Using these populations as new laboratories requires at least an order of magnitude gain in S/N
- **LAD** FoV is matched to discovering and studying pulsars in active regions within the Magellanic Clouds, M31, and whole dwarf galaxies such as IC 10, and others in the local group.
- **SXRC** with superior S/N can look for pulsations in all Galactic transients, and in luminous extragalactic sources, HMXBs and ULX
- Populations offer the chance to perform controlled “experiments”, by accumulating statistical samples of objects.
  - Spin and orbital period distributions
  - Pulse profile modeling of large statistically selected samples
  - other fundamental parameters that can be indirectly inferred such as rotational inertia, magnetic field, radius.
- Cyclotron lines and other features, potentially in single pulsations\*
- Dips and Eclipses, disk precession
- Impact of transient sources on Luminosity distributions
- Orbital modulation and QPOs in ULX
- **Rare states become common when the target volume expands**



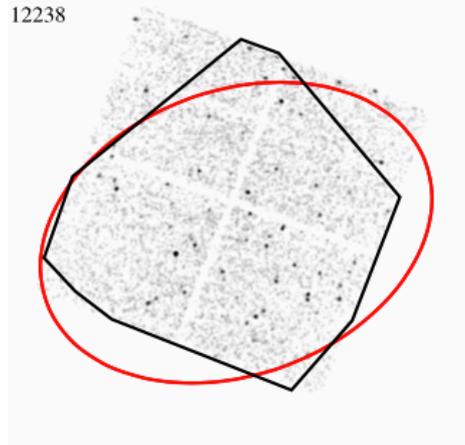
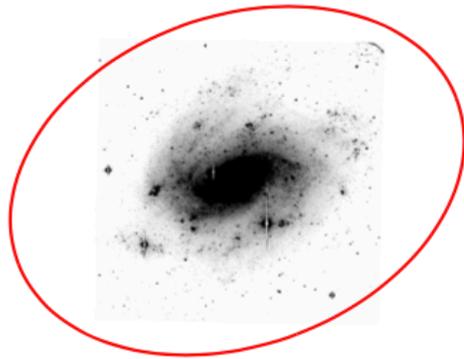
# HMXBs and their progenitor populations I



- HMXBs trace Star Formation Rate
- Universal Scaling law, variation with environment/metallicity? Brorby, Prestwich+ 2015
- Cosmological Probe
- Space density – calibrate population synthesis
- But! Response Time? Number Density?, Duty Cycles? Why??? -> Time Domain

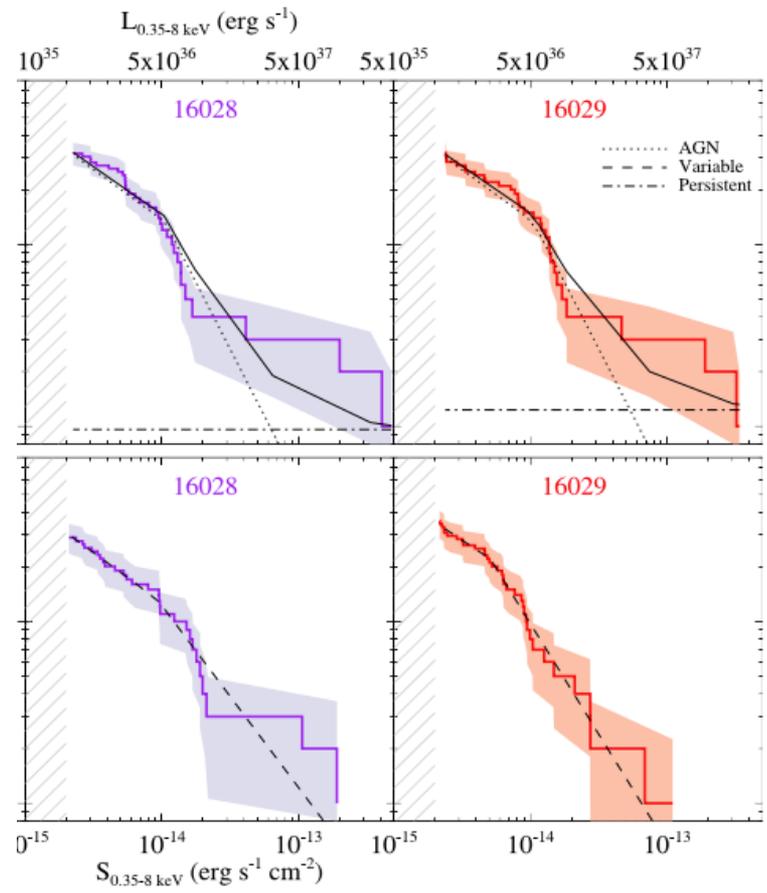
# Luminosity functions and variability: HMXBs in NGC 300

ground-based, R-band



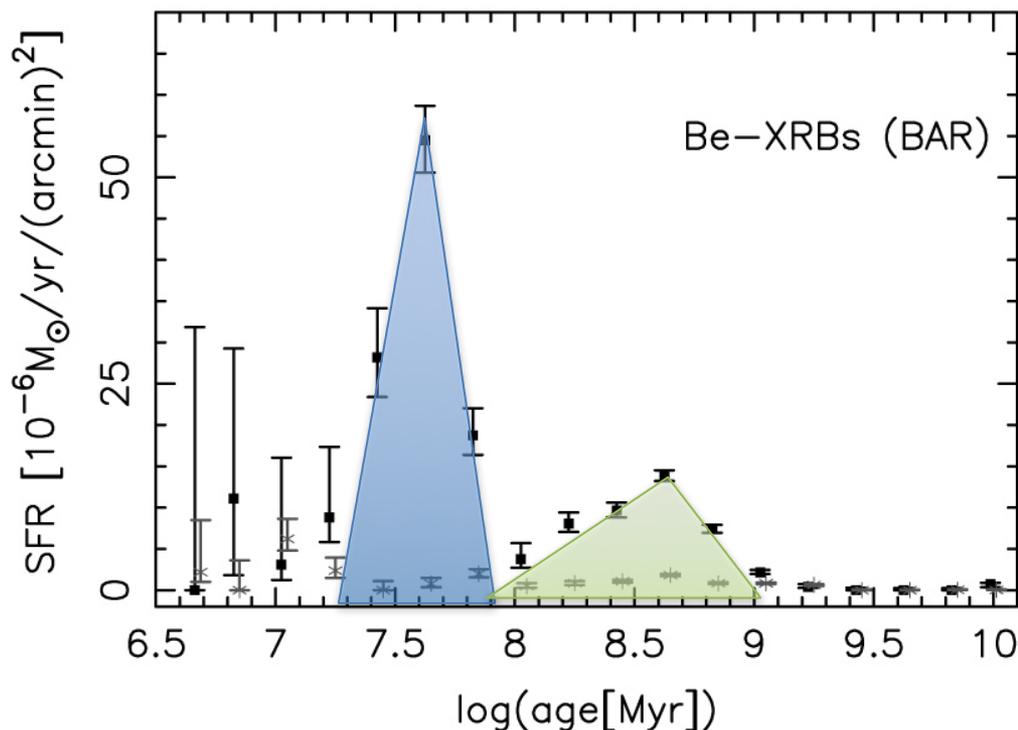
3 epochs of 184 ksec  
Separate LogN-logS composed for persistent  
and variable sources.

Modeling of LogN-logS using different  
outburst templates to recreate the observed  
distributions indicates that HMXB in type II  
outbursts dominate the transients



# HMXBs and their progenitor populations

## Galactic Archaeology



SMC  $\sim 40$  My peak

LMC  $\sim 20$  My

IC10  $< 10$  My ?

Why? Metals  
Rotation  
Mass loss

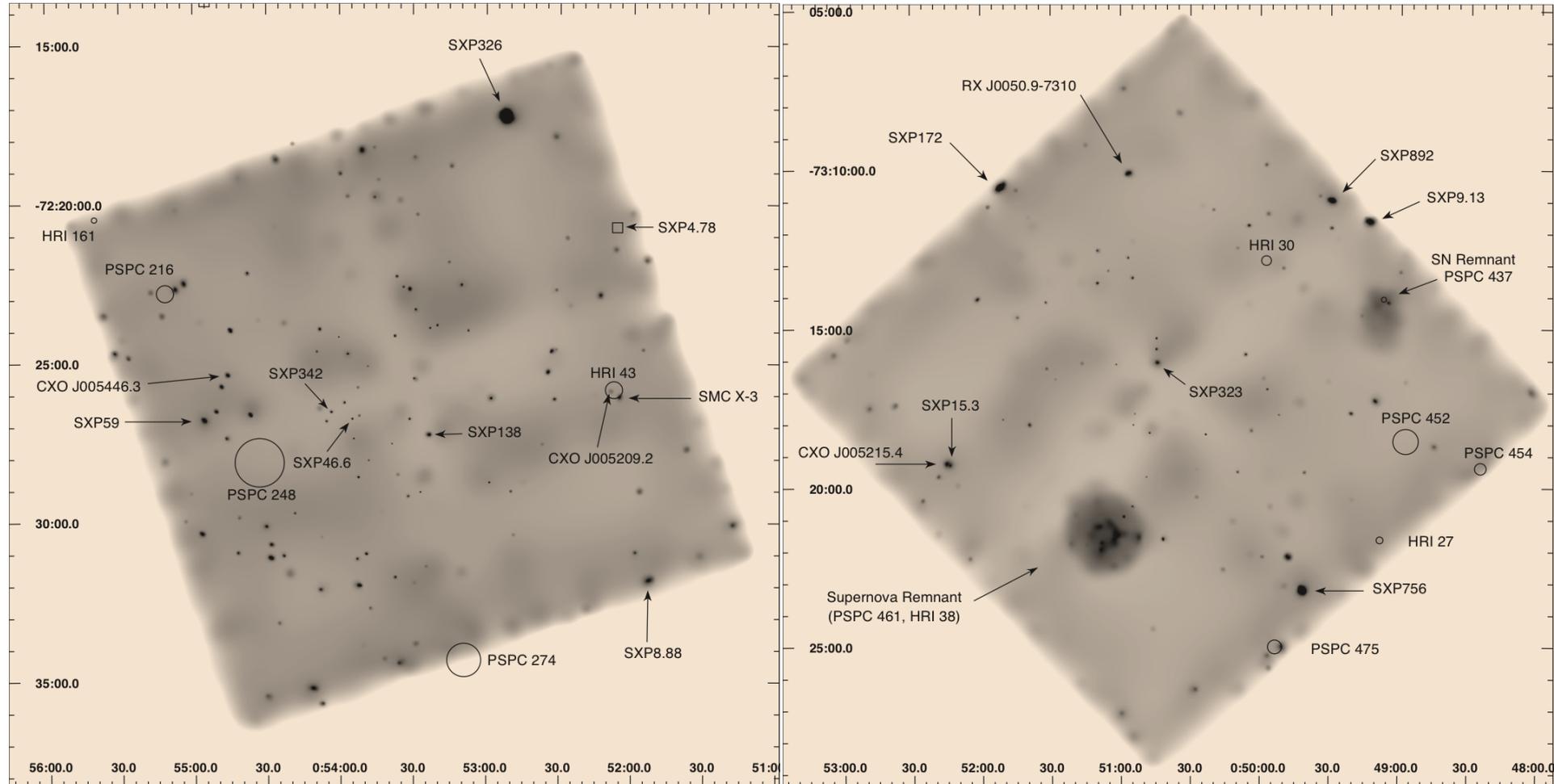
The angular resolution of Chandra enabled large-scale identification of optical counterparts. Leading to some spectacular science.

E.g. Antoniou et al., 2010, ApJL, 716, L140,

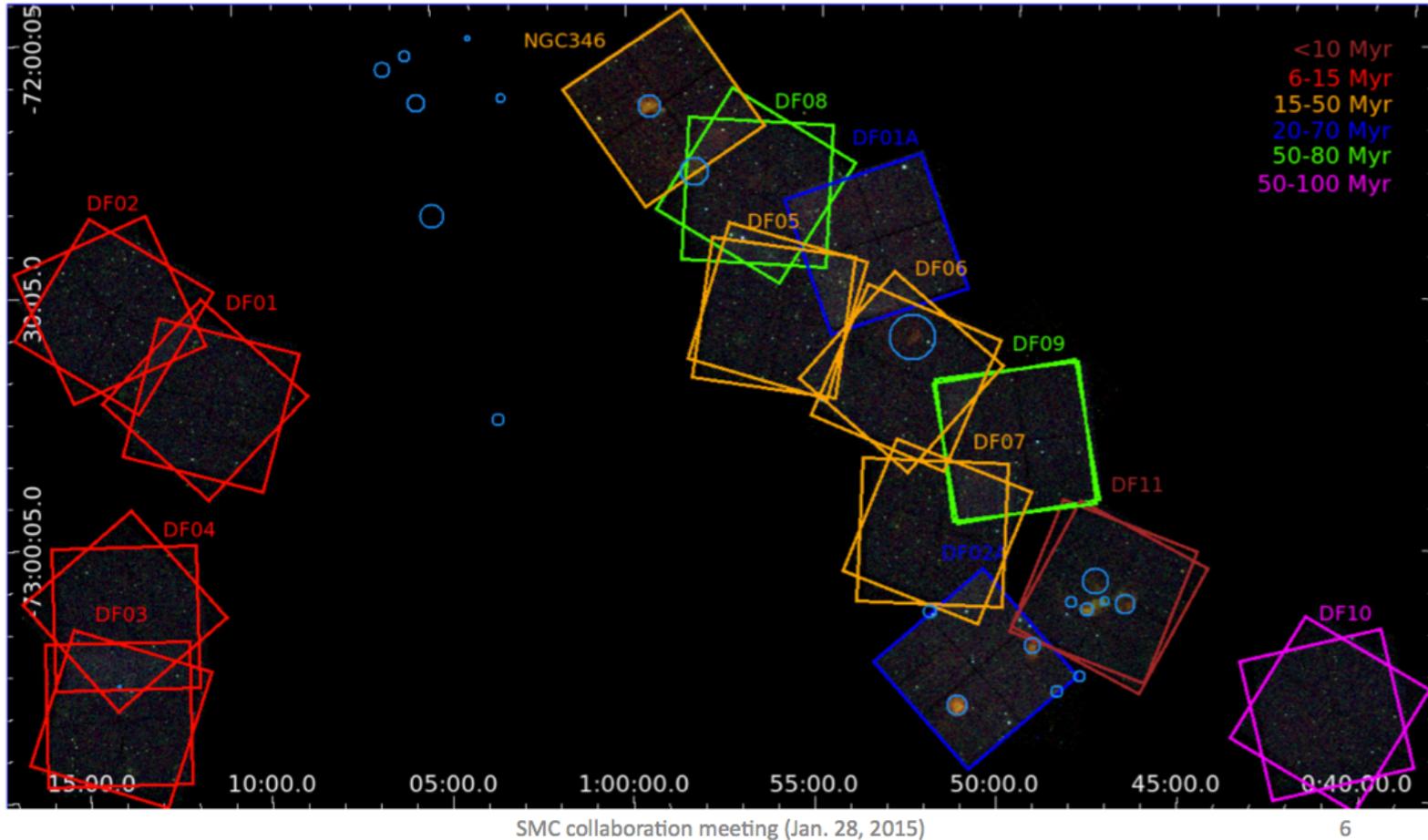
Antoniou & Zezas 2016, 2017

# SMC Deep Fields

394 sources, 15 pulsars, How Many HMXBs? Quiescence?, long  $P_{\text{spin}}$ ?, limits of  $L_x$ ?



# X-ray Visionary Project. A Case Study of X-ray Populations at Low Metallicity.



11 Chandra fields observed for 100 ksec each. Targets age-selected regions of the SMC. Contains ~3000 X-ray point sources. Zezas+ 2017, Hong + 2017a,b, Antoniou+ in prep.

# Evidence for HMXBs in IC 10

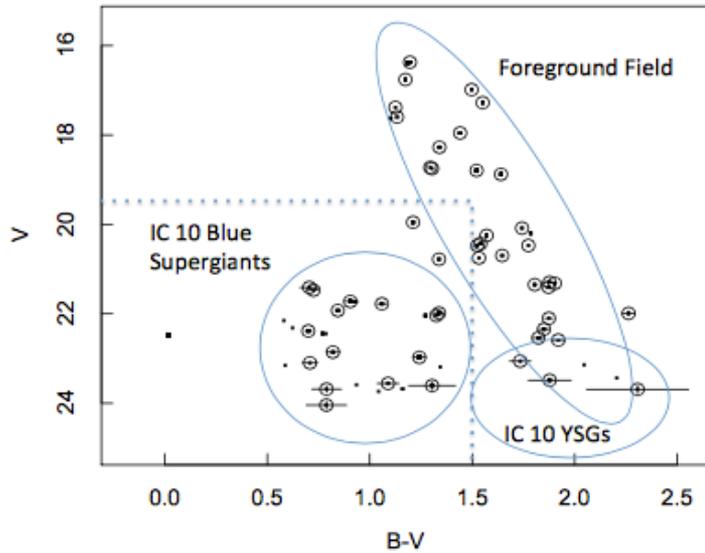
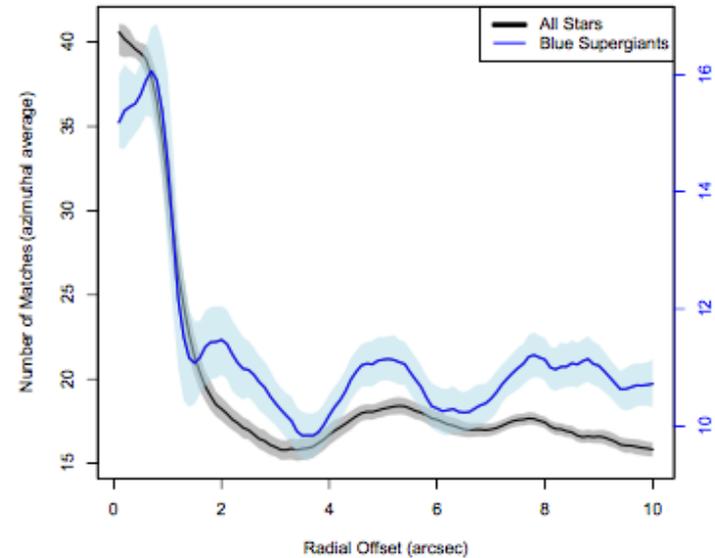
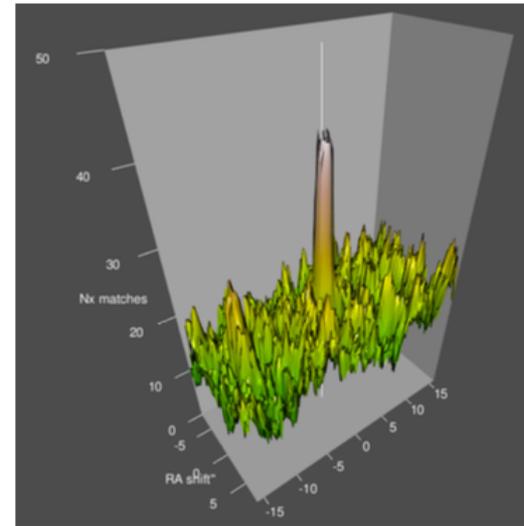
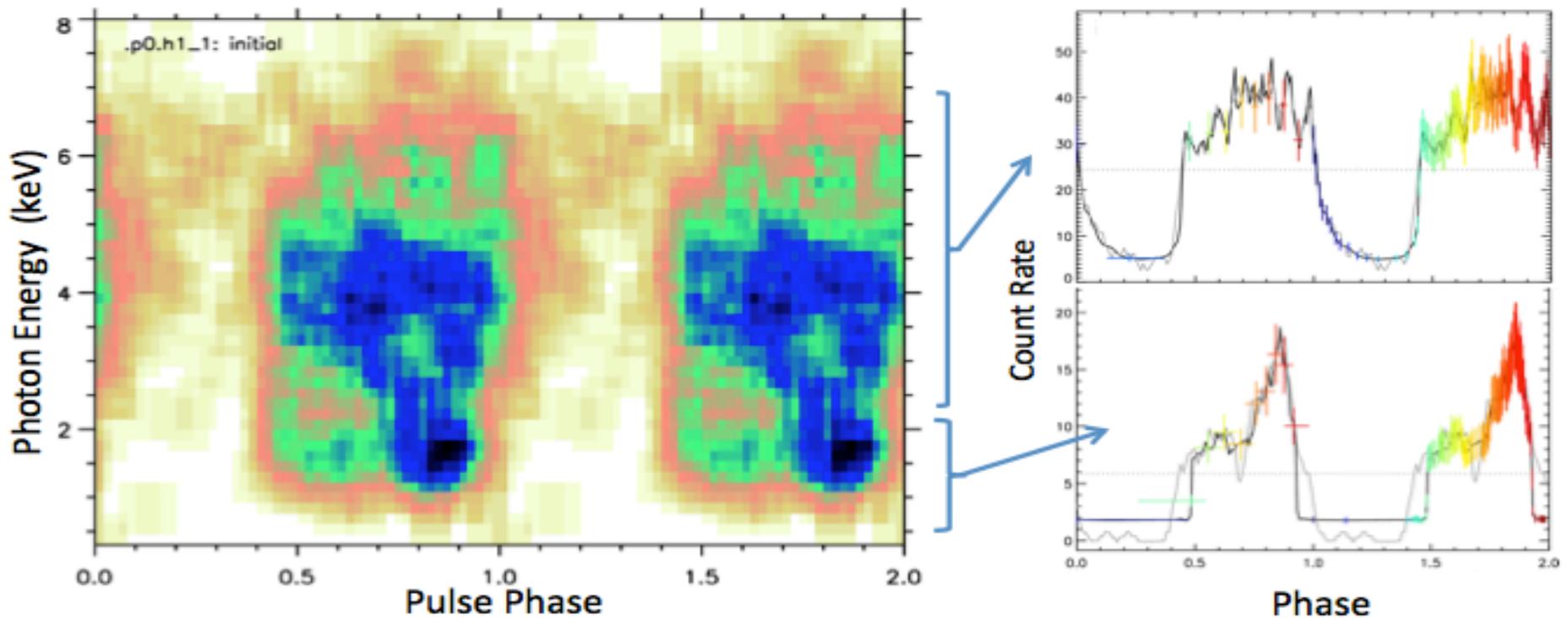


FIG. 1.— Color-Magnitude diagram for positional counterparts to Chandra X-ray sources in the IC 10 field. Ovals indicate the locii of BSGs in IC 10 and the foreground Galactic population which lies atop the yellow SG track for IC 10 (comparison with Massey et al. 2007, Figure 14). A few objects have multiple counterparts; then the one at the smallest offset is retained and the others are indicated by a smaller dot symbol. Dotted lines show the selection  $B-V < 1.5$ ,  $V > 19.5$ .



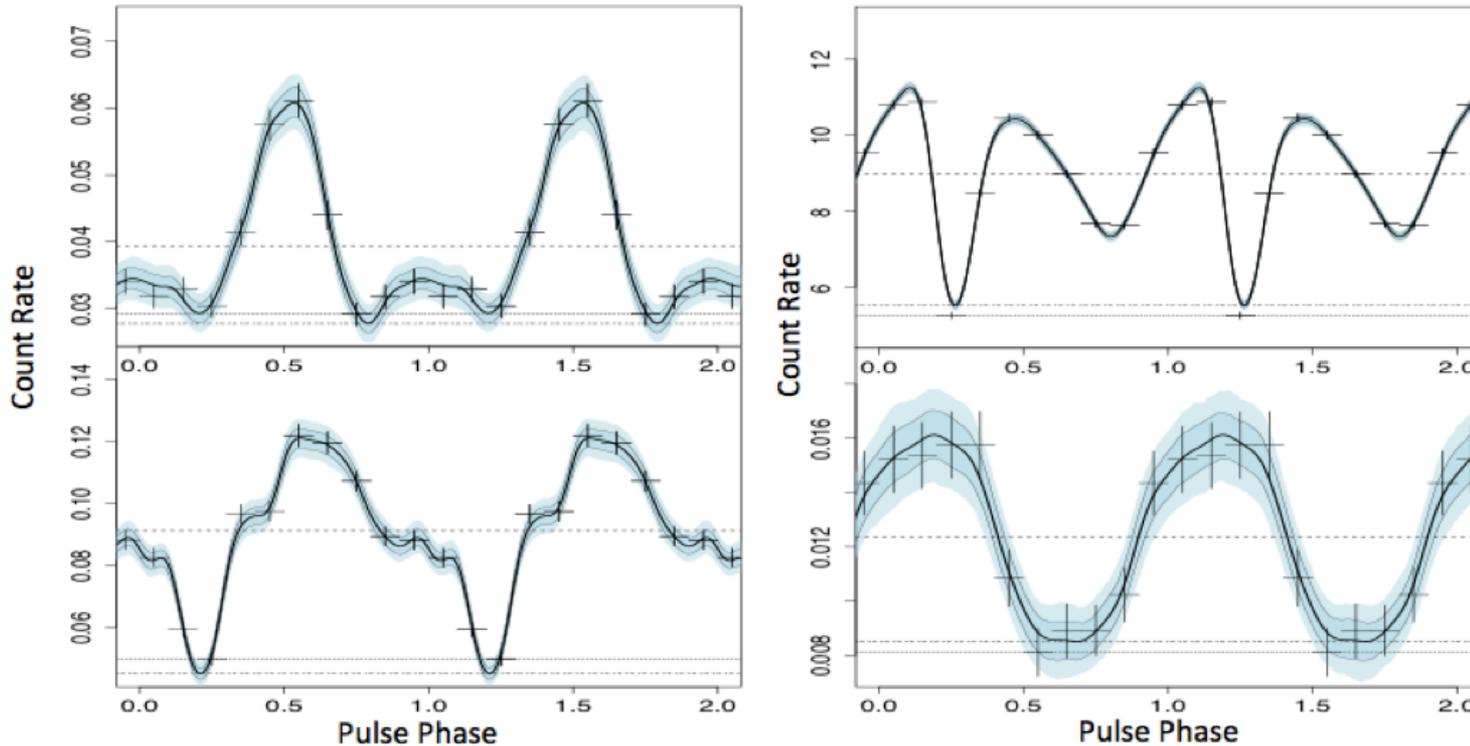
This is the type of data we would like to obtain on coherent timescales



Chandra ACIS Event file for SXP represented as a Phase-Energy-Intensity map. We see a broad plateau-like component above 3 keV, while a sharp feature (sharp in both phase and energy) is seen centered around 1.5 keV (Hong+ 2016, ApJ, 826, 8)

This is a 100 ksec Chandra exposure – during that exposure the source properties changed dramatically. To correctly reconstruct the map, STROBE-X must deliver such data within a “coherence time” of certainly < 10 ksec, ideally on per pulse basis – possible for galactic systems!

# Pulse Profile Reconstruction



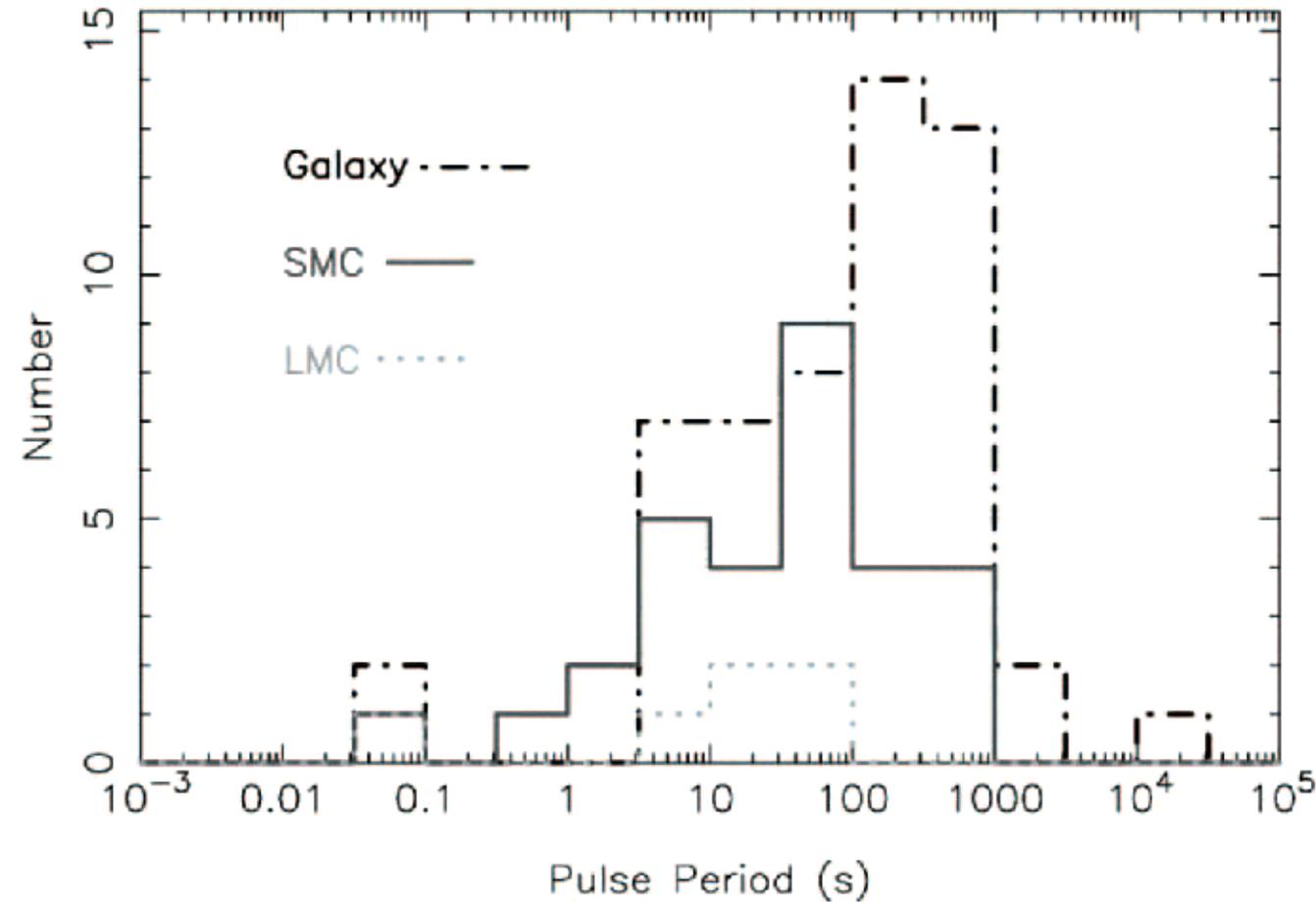
Profiles are heavily modified by the light-bending properties of GR. Three facts are clear:

- Pulse profiles exhibit a diverse range of morphology.
- A pulsar's pulse-profile can change shape dramatically.
- The profile is different when viewed in different energy bands, even to the extent of completely reversing its phase.

Before more progress can be made in modeling the NS polar cap structure and the radiative transfer processes in the accretion column, the community needs certain information:

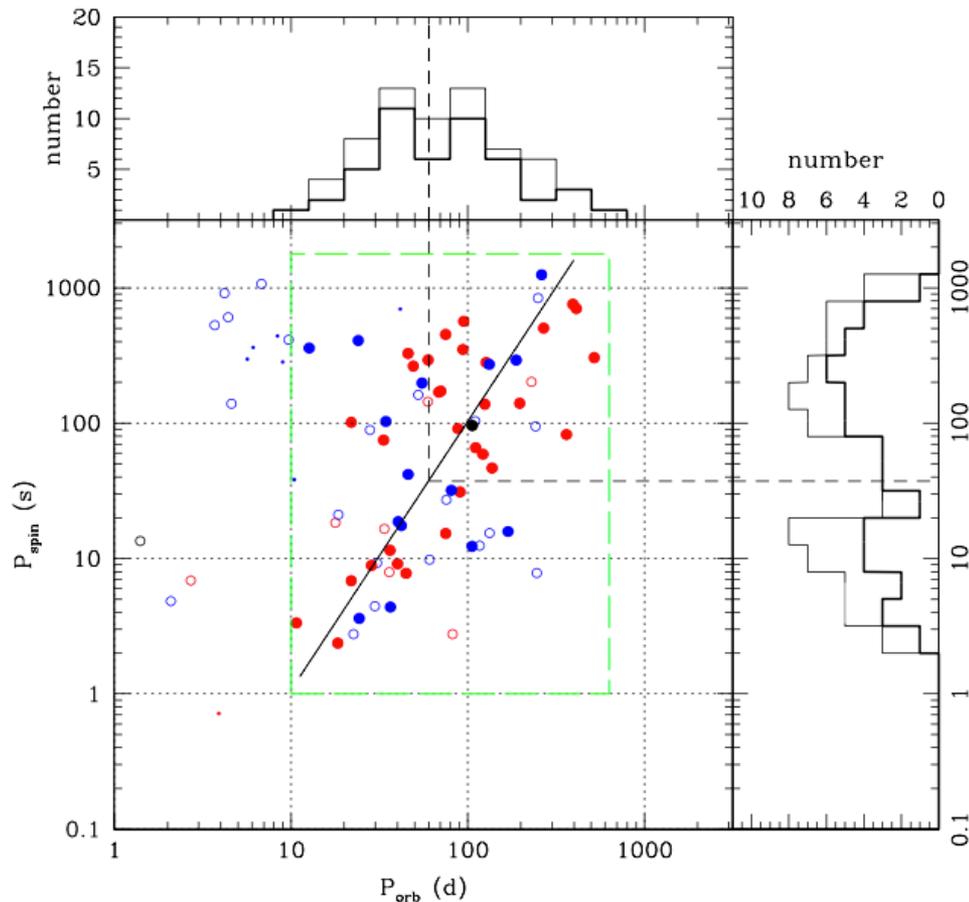
- What universal emission structures can be uniquely identified from pulse profiles?
- What systematic changes are driven by accretion rate, and can a 'fundamental plane' relationship be found linking them across all pulsars?
- How does pulse profile morphology vary with photon energy, and under what conditions?

# Distribution of Pulsar Spin Periods



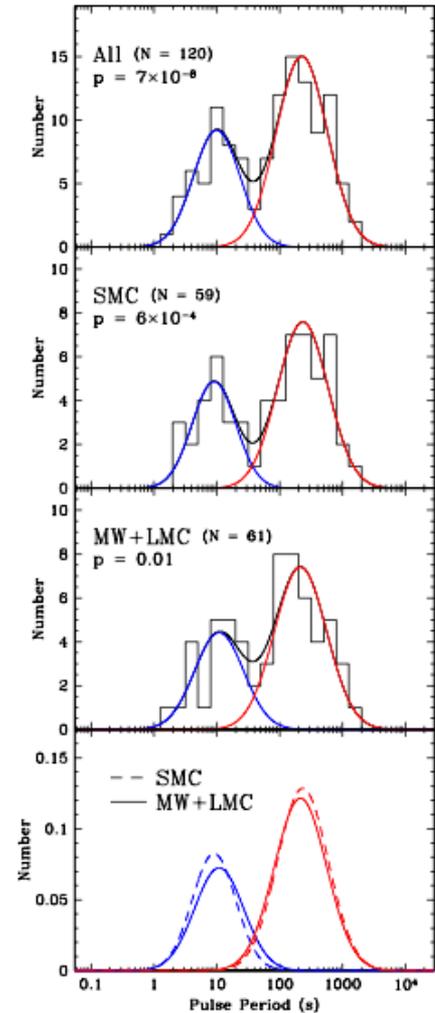
- Do not resemble neutron star birth spins
- Preference for  $\sim 100$ - $200$ s
- Upper and lower limits?
  
- Both limits are driven by evolution and plasma physics

# Why study Pulse period distributions?

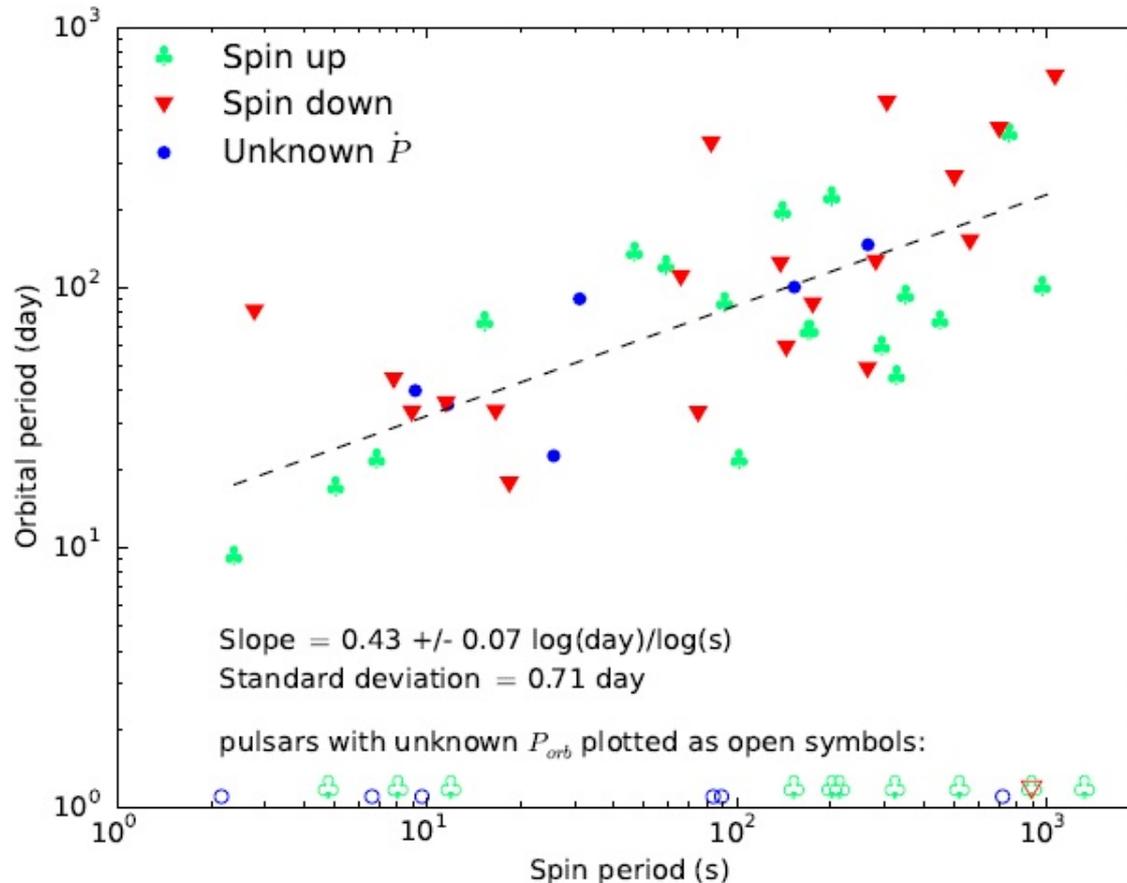


Knigge, Coe, & Podsiadloski, 2011, Nature,

Are there 2 distinct formation channels or NS, or is something else going on?



# Filling in the gaps in the period distribution



Yang+ 2017 show that the majority of SMC pulsars appear close to equilibrium spin, with Roughly 1/3 long term spin up, down, and constant within errors. See also Ho & Klus calculation of B fields based on torque balance.

# Spin-Orbit Equilibrium for X-ray Pulsars

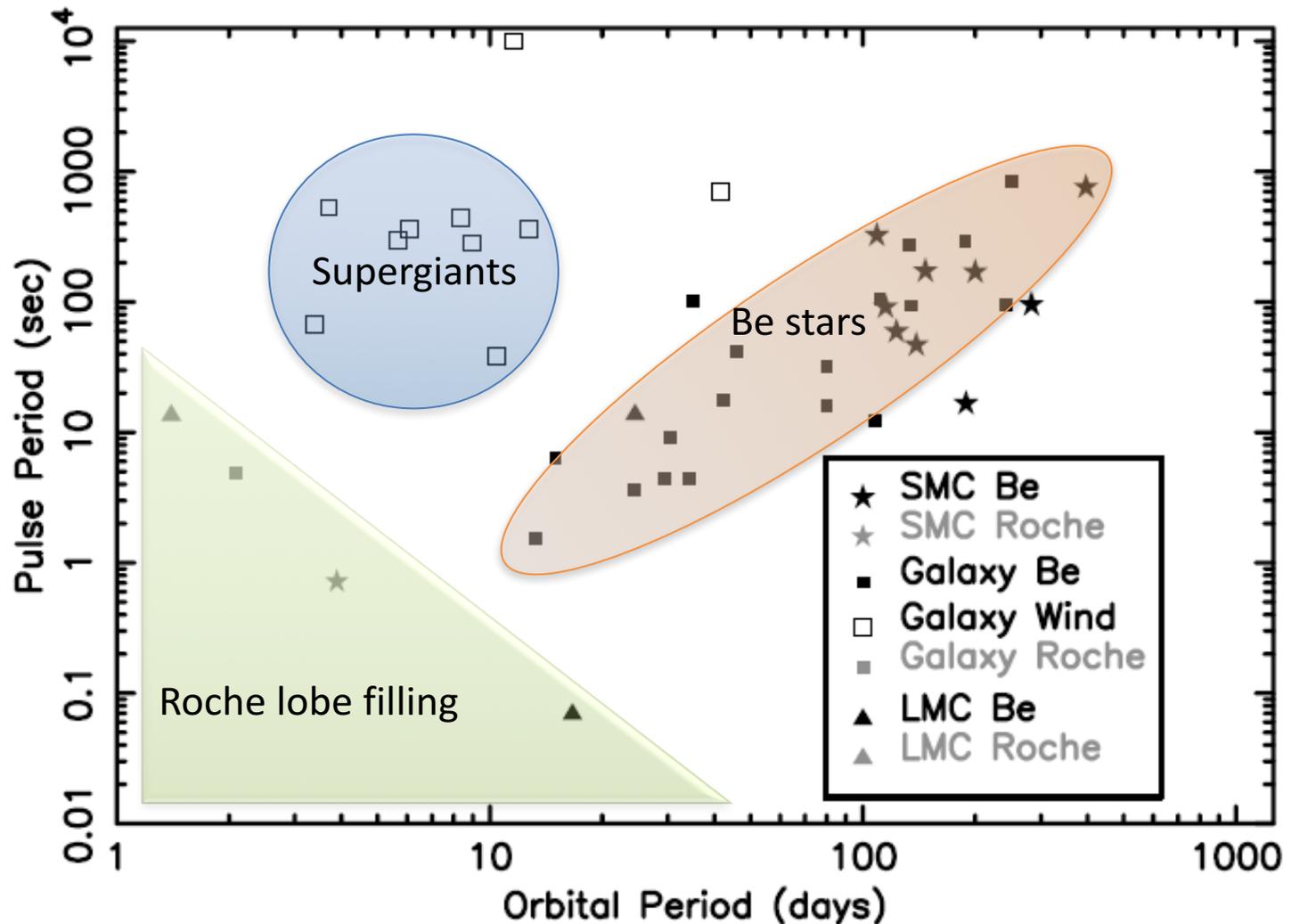
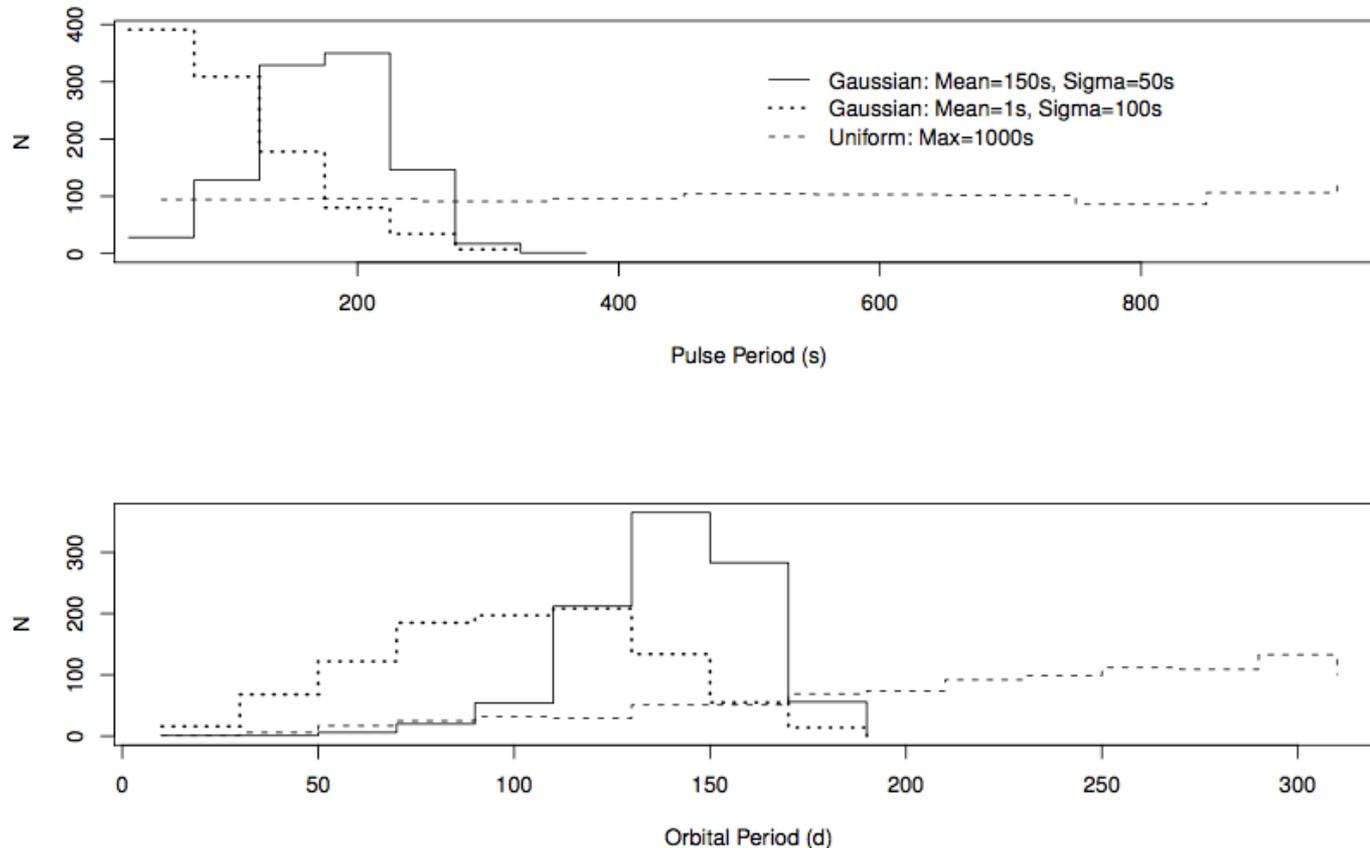


Figure from Laycock et al. 2005, see also Corbet 1984.

## What do we know about the underlying Spin Period Distributions?

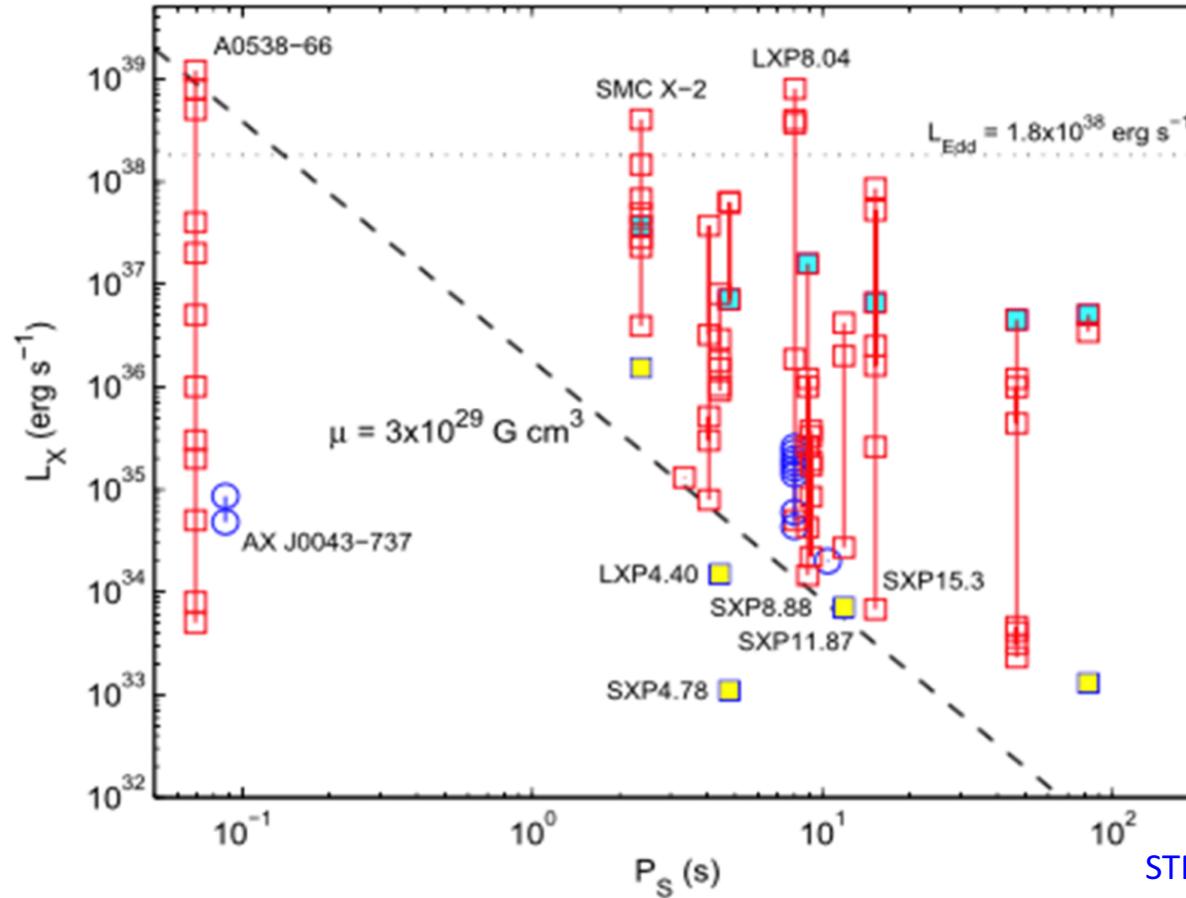


Spin and orbital period distributions are thought (on strong observational grounds) to be coupled. However the observed distributions are incomplete, and there is good reason to suppose that biases mask the underlying picture.

FIG. 2.— Model Period Distributions. The upper panel shows 3 example  $P_{pulse}$  distributions, while the lower panel shows the resulting  $P_{orbit}$  distributions assuming the two are coupled by Equation 13, as inferred from the Corbet diagram.

Can we get at Nascent spin distributions? Faucher-Giguere & Kaspi (2006, ApJ, 643, 333) lie between 11 and  $\sim 100$  ms. Miller et al, (2011, ApJ, 731, L5). Haberl

# Controlled population experiment I. Population $P_{\text{spin}}$ vs. $L_X$ Parameter Space



*Christodoulou (2017a)*

Assuming a universal value of  $\mu = BR^3/2$   
We fit the lower envelope of the pulsed points, resulting in  $\mu = 3 \times 10^{29} \text{ G cm}^3$ , corresponding to  $B = 6 \times 10^{11} \text{ G}$

Under assumption of canonical  $M, R$

STROBE-X will greatly improve this technique

$$L_{X,min} \approx 2 \times 10^{37} \left( \frac{\mu}{10^{30} \text{ G cm}^3} \right)^2 \left( \frac{P_S}{1 \text{ s}} \right)^{-7/3} \left( \frac{R}{10 \text{ km}} \right)^{-1} \left( \frac{M}{1.4 M_\odot} \right)^{-2/3} \text{ erg s}^{-1}. \quad (1)$$

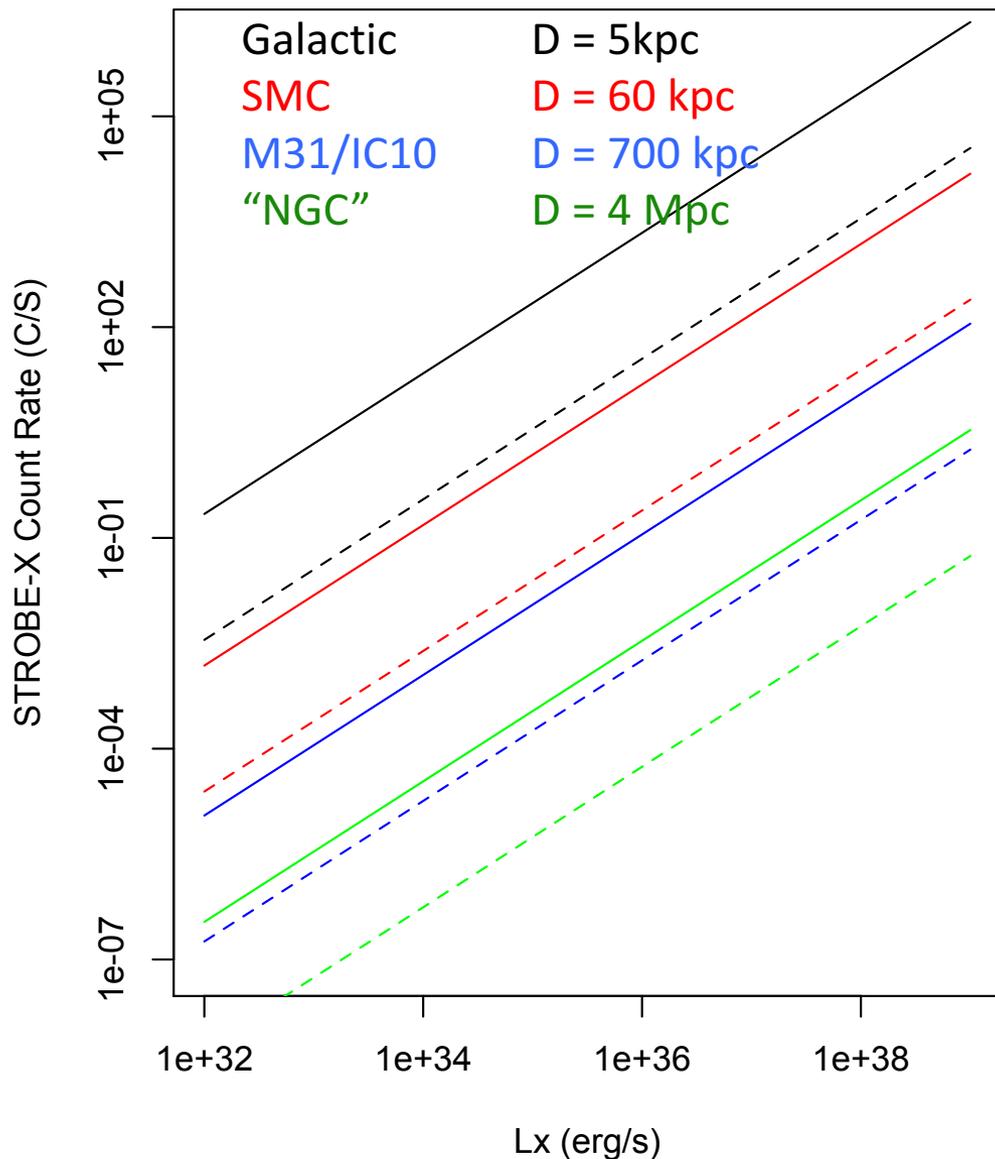
For the typical pulsar parameters for  $M$  and  $R$ , eq. (1) reduces to the form

$$L_{X,min} \approx 2 \times 10^{37} \left( \frac{\mu}{10^{30} \text{ G cm}^3} \right)^2 \left( \frac{P_S}{1 \text{ s}} \right)^{-7/3} \text{ erg s}^{-1}, \quad (2)$$

## The control parameters for X-ray outburst in HMXB pulsars

- On the longest timescales, evolution from the propellor to the accretor regime points to a time-lag between NS formation and pulsar turn-on, as manifested in the question, how are the slow pulsars produced inside the lifetime of a Be star? (Ikhsanov, N. R., 2007, MNRAS, 375, 698)
- Accretion torques on short timescales, combined with the long-term spin derivative provide one answer (Ho and Klus, Townsend+).
- Cyclotron lines provide another (Kretschmar+, Pottschmidt+)
- Meanwhile Cyclotron line and  $\dot{P}$  are not being measured for the same pulsars!
- STROBE-X is a single observatory capable of doing both simultaneously
- For rapid rotators the accretion barrier is higher, perhaps so high that a reservoir of matter is required. The rare outbursts of the sub-10 second pulsars.
- STROBE-X must have exquisite time resolution and be able to maintain this at high count rates. Loss of spectral resolution would be an acceptable tradeoff.
- What about a high rate mode dual mode delivering broad band timing at “event resolution” and a simultaneous spectra accumulated onboard at lower time resolution (say 1 second).

# The HMXB discovery space for STROBE-X



PIMMS simulation\*  
Powerlaw index = 1.5  
NH =  $10^{21}$  atom/cm<sup>2</sup>

XRCA = 20 x NICER  
LAD = 12 x RXTE PCA

**Galactic Systems:**  
**Phase resolved spectroscopy of Individual pulses!**

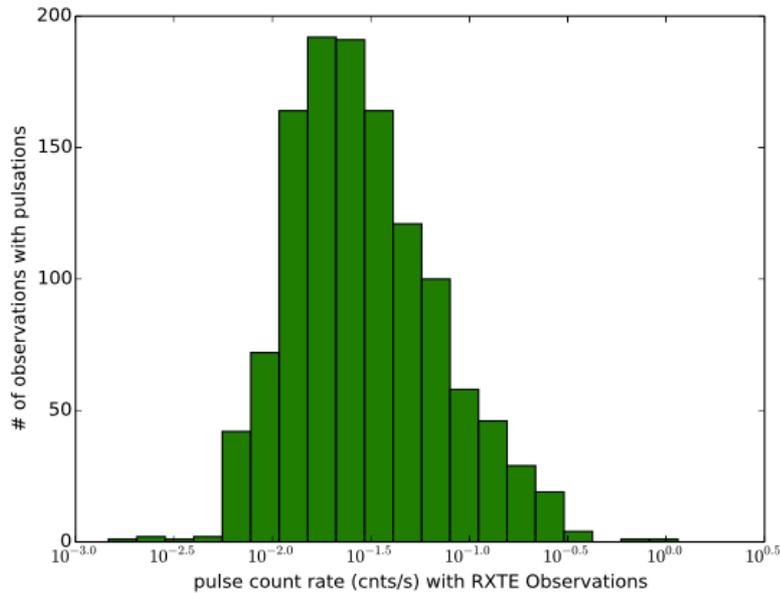
**Magellanic Clouds:**  
**Individual pulses during outbursts**

**Pulsar hunting in Local Group:**  
If Pulsation detectability per orbit (200 counts in 5 ksec) approx.  $6.5 \times 10^{-15}$  erg/cm<sup>2</sup>/s we can  
At SMC this is  $2.6 \times 10^{33}$  erg  
at M31 its  $3.6 \times 10^{35}$   
at 4 Mpc its  $1.2 \times 10^{37}$

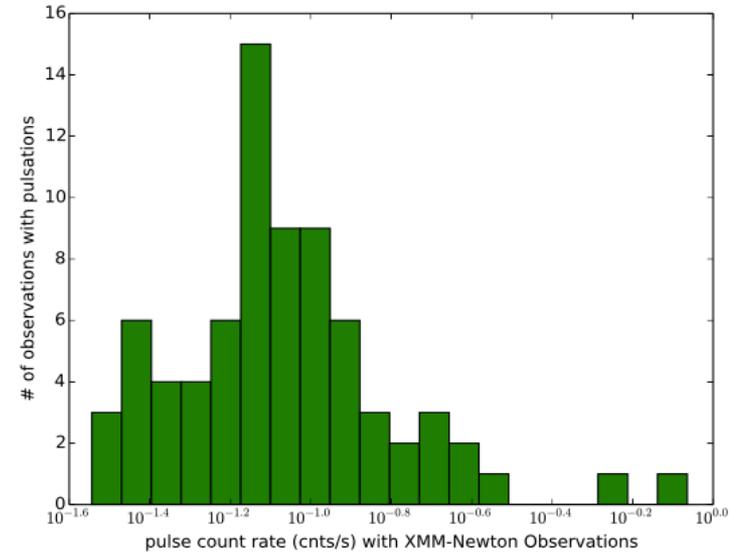
(Factor of 4 fainter for 1000 counts in 100 ksec)

(Subject to background)

# Counts rates needed to detect pulsations



**Figure 8.** Similar to Fig. [6], showing the frequency histogram of pulse amplitude for pulsations with  $s \geq 99\%$  detected by *RXTE*.

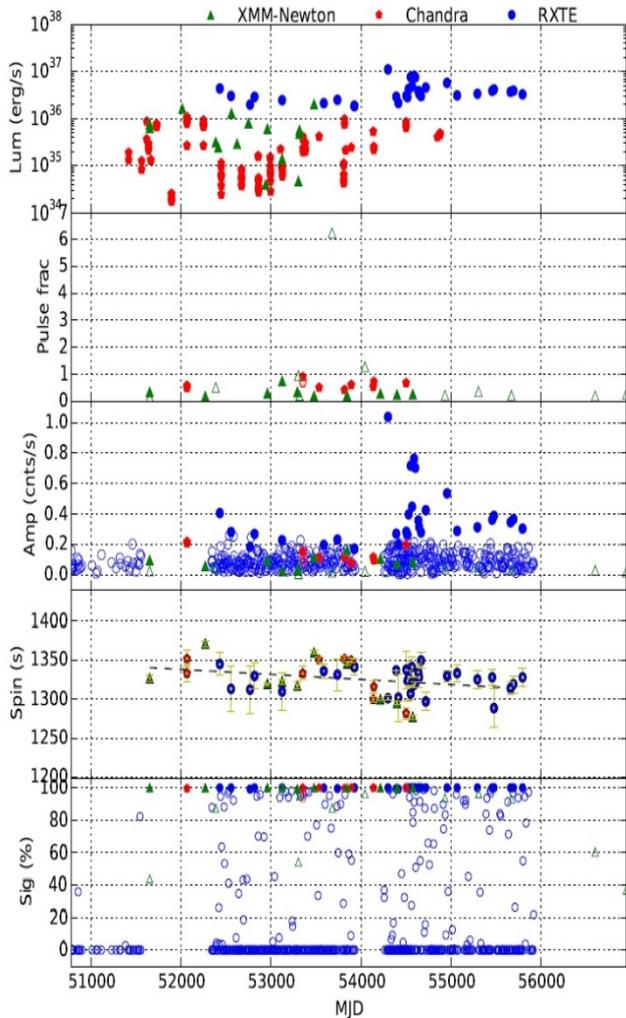


**Figure 6.** Histogram of the number of *XMM-Newton* observations in which pulsations were detected with  $s \geq 99\%$  as a function of pulse amplitude in terms of count rate binned on equal logarithmic intervals.

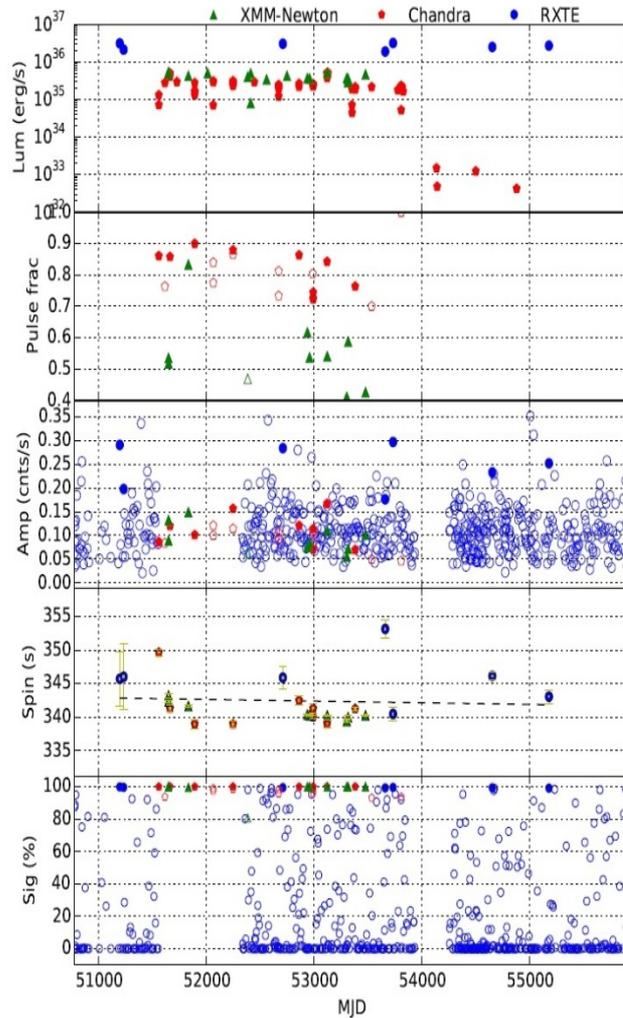
$\log_{10} A \simeq -1.2$  (or 0.06 count/s) for both ACIS and PN, and for the *RXTE* amplitude histogram a similar turnover occurs at  $\log_{10} A \simeq -1.7$  (or 0.02 count/s.)

Similar analysis using the net counts, suggests  $>200$  counts are typically required for a 99% significant detection

# X-ray binary pulsars on all timescales



SXP 1323



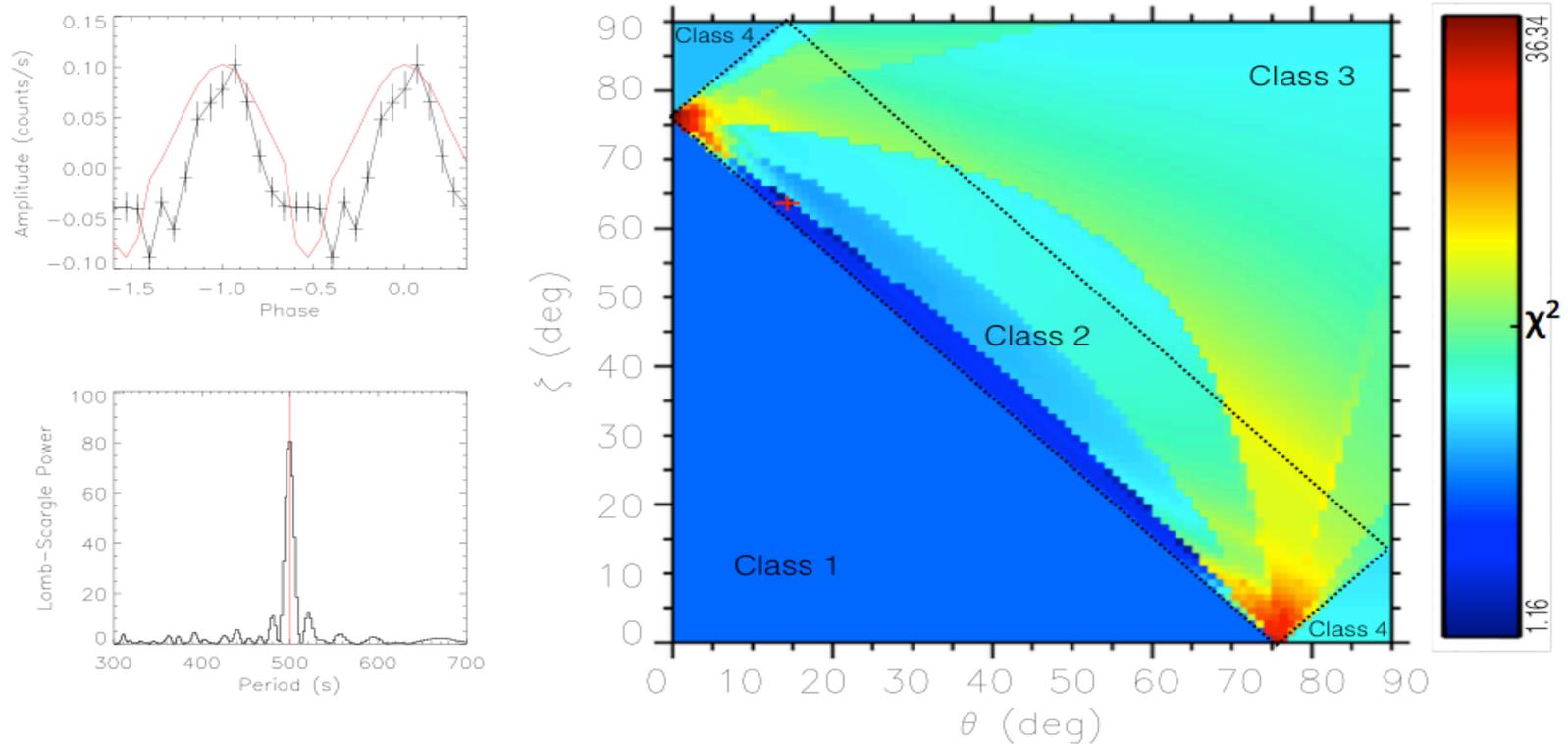
SXP 348

*Yang + (2017)*

STROBE-X could revolutionize this type of long duration study by following the profile of a large number of complete outbursts.

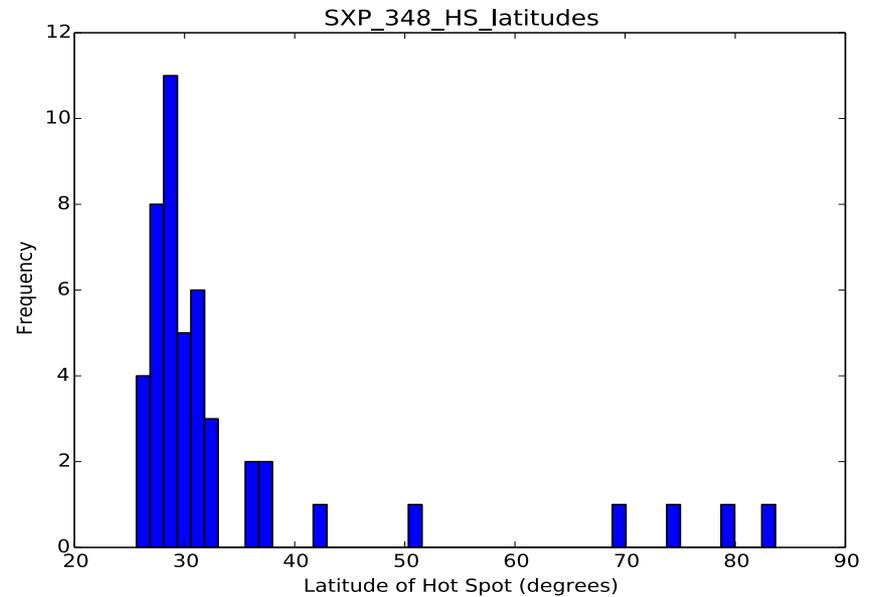
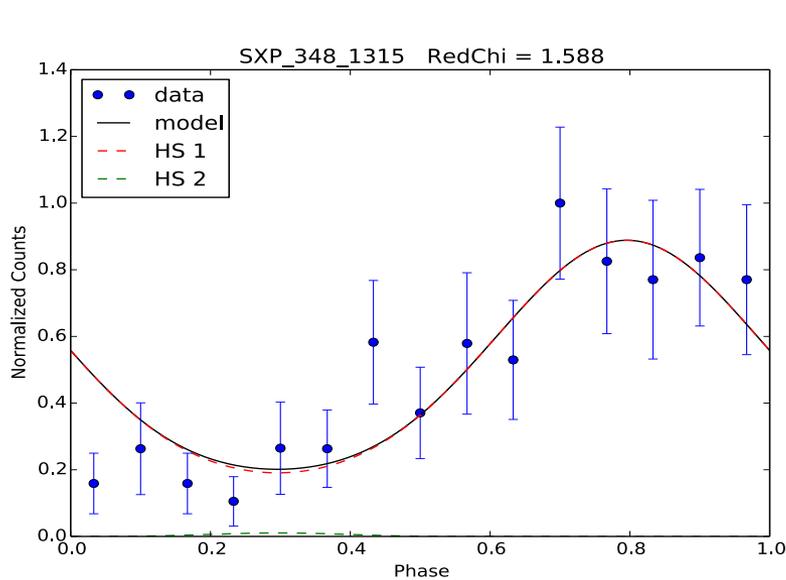
Timing accuracy sufficient to track accretion torques and orbital motion for many more systems

## Pulse profile modeling – are simple models useful? and do simple pulsars exist?

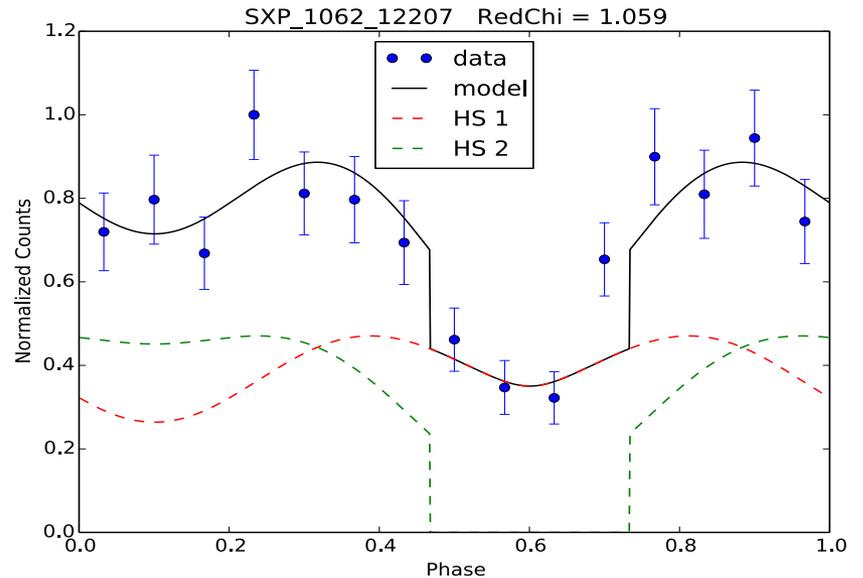
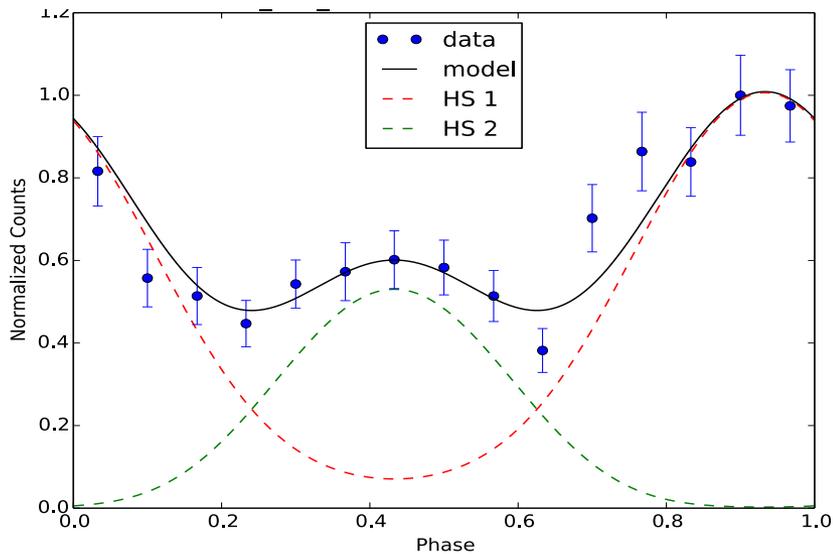


Above an antipodal pair of isotropically emitting hotspots are fit to a single pulse profile, including gravitational bending of the rays. A goodness-of-fit map shows the chi-squared values for combinations of the inclination angle of the spin axis, and the magnetic dipole offset angle. Compactness  $M/R$  is also a fit parameter. Classes 1-4 refer to Beloborodov (2002) description of one, both, or an alternating combination of hotspots are visible.

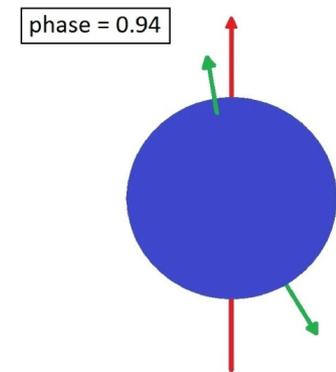
# Controlled Statistical experiments with pulsar populations



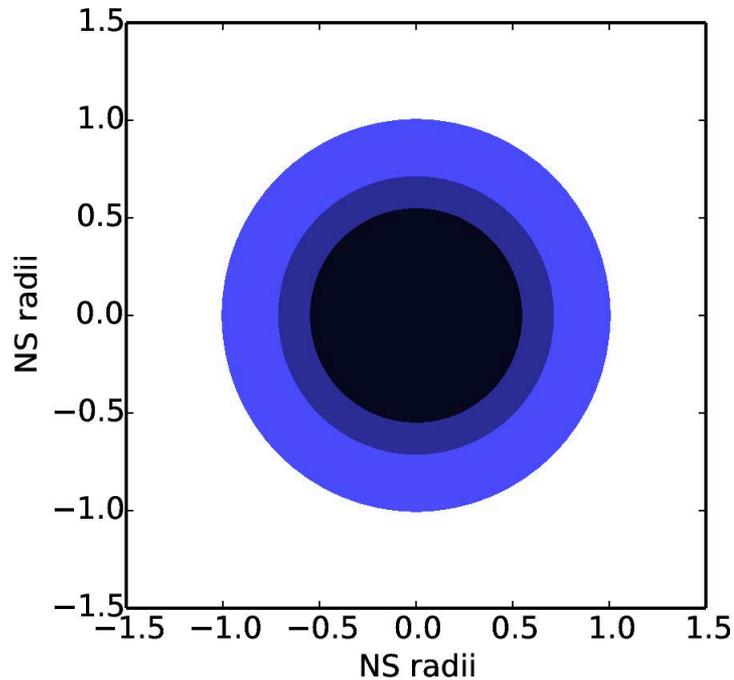
Fitting all library pulse profiles obtained for the same pulsar we assemble the histograms of each model parameter. Shown at right is the histogram for magnetic dipole offset angle. A certain value is strongly preferred during most observations, suggesting that we are measuring this fundamental parameter.



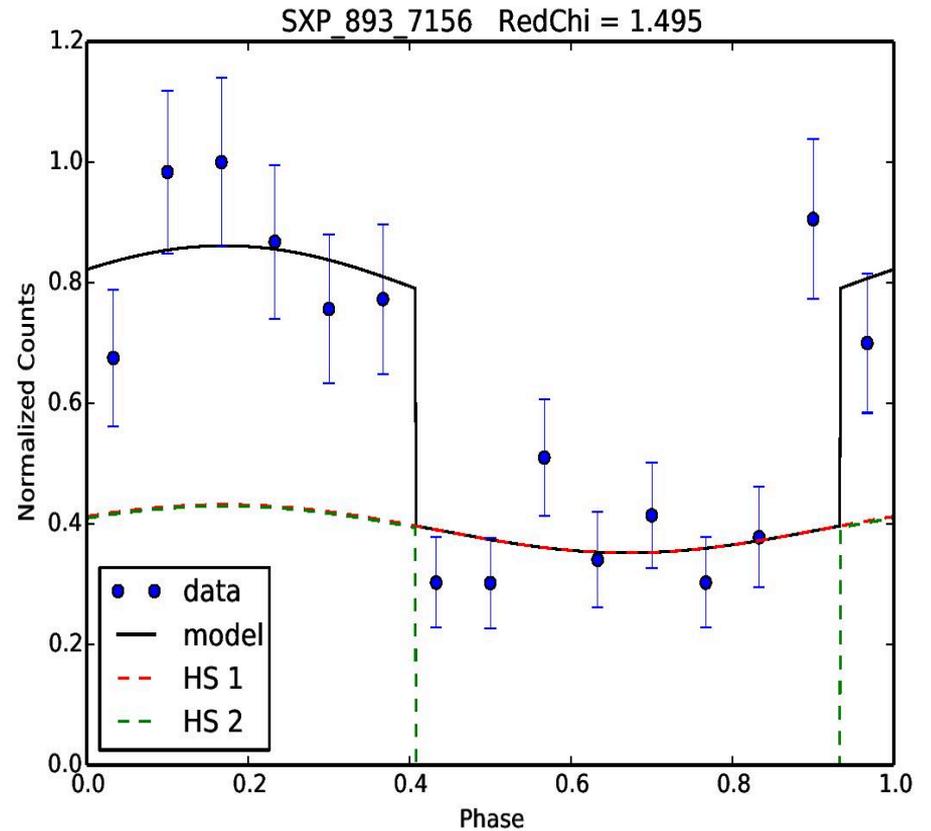
Polestar fits to a XMM-Newton pulse-profiles illustrating some differences between pencil-beam (left) and fan-beam (right) dominated morphology. The fan-beam component reproduces the abrupt drop in flux as the more distant hotspot crosses the terminator. Cappallo et al., (2017). Polestar can be run interactively at <http://polestar.live>.



# Fan Beams Crossing the Terminator



The visible portion of the far side of a NS. The black denotes the terminator for a canonical NS.



An example of a profile with a sharp cutoff fit with a fan beaming function. Cappallo+ 2017 in press. **See also Falkner+ 2016 for a different possibility**

## Don't we have enough pulse profiles? (no)

- The entire archive of X-ray Pulse profiles numbers in the thousands.
- This number masks a hole.
- If we ask how many high S/N profiles exist, the number shrinks dramatically.
- Our definition of “high S/N” need not be totally arbitrary. In order to quantify (and not merely set constraints on) the energy dependence of the profile, requires on the order of 10,000 counts, if we add phase dependence at physically interesting timescale, that rises to perhaps  $10^6$ .
- As in the STROBE-X proposal, modeling a pair of smooth isotropic hotspots can yield M/R, and hence the EOS. Other fundamental findings can also be made: e.g the magnetic axis angle.
- The majority of accreting pulsars do NOT produce such idealized profiles however, and other physics comes into view.

### **Known Unknowns in Pulse Profile Modelling:**

#### **1. What is the origin of abrupt drop-out features?**

- eclipses by the accretion stream
- terminator crossings of fan-beam like emission

#### **2. How much profile-to-profile variation exists?**

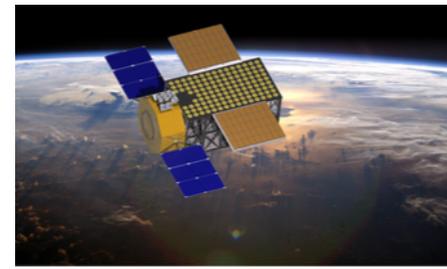
- What can it reveal about the dynamics of the accretion stream?
- Are there preferred radii due to magnetic field etc.

#### **3. What control the onset of energy dependent phase features ?**

#### **4. How does the pulse profile evolve during an outburst, and are there distinct classes of accretor with their own preferred magnetic field and accretion geometry.**

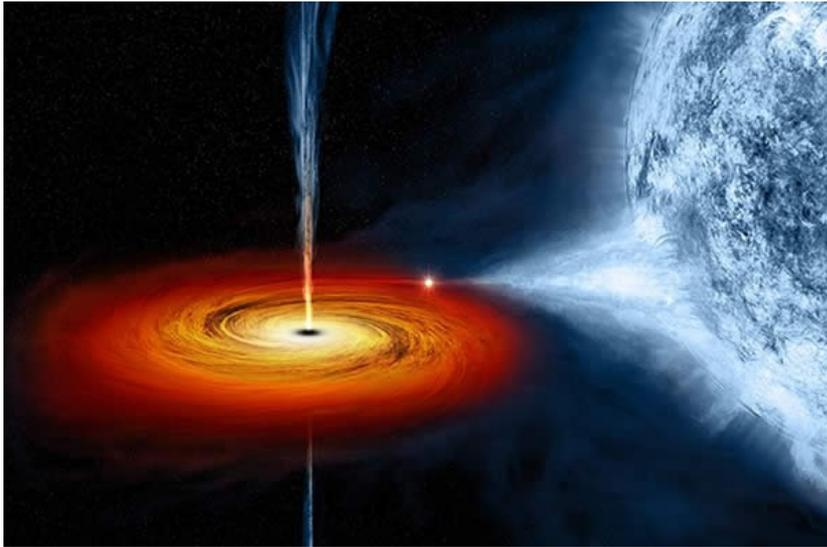
- Only a tiny minority of pulsars have ever been observed through an outburst
  - Due to sensitivity thresholds
  - Due to lack of triggering
  - Due to scarcity of dedicated monitoring mission

# Summary



- STROBE-X is a revolutionary instrument for HMXBs in external galaxies (MCs & beyond) because it is a whole galaxy monitor.
- SXC + LAD will capture features in pulse profiles that have only ever been seen in stacked averaged observations
- Combination of broad energy range, huge EA , and time resolution are far more important than spectral resolution.
- Real controlled experiments using statistically meaningful samples of pulsars across B-field,  $P_{\text{spin}}$ ,  $P_{\text{dot}}$ , magnetosphere morphology,  $L_x$  will be possible
- Current work points to a host of known unknowns
- Will be extremely symbiotic with planned Polarization missions
- LOFT White paper lays out additional detail

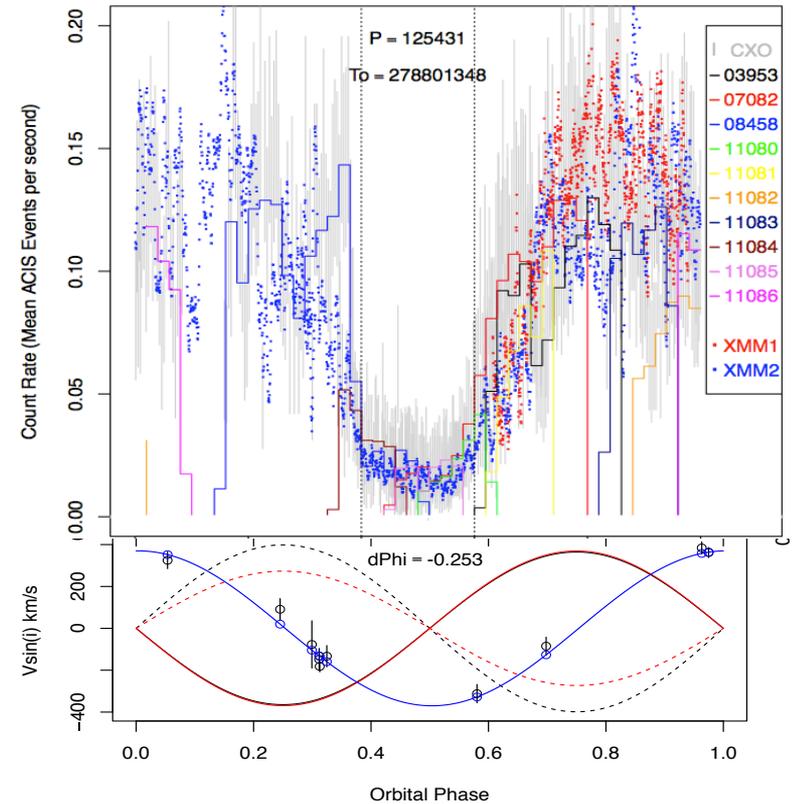
# BH HMXBs



BH HMXBs are a key class of object for understanding GW event rates, and understanding the mass function of double degenerates. Recent work on IC 10 X-1 and Cyg X-3 point to the need for new capabilities: ability to resolve X-ray absorption and fluorescence lines in integrations of one hour and less. Steiner et al 2016, Laycock 2015, Barnard 2015 collectively pushed XMM/Chandra to the limit of what can be accomplished, and opened a big can of worms in the process.

Velocity resolution (McCullough, Hainikainen, etc) however will remain in the realm of gratings and micro-calorimeters.

Similarly at the HEAD meeting we heard from Marianne Heida that phase relationship in the archetype BH XRB between various multi-wavelength timing features does not support the accretion geometry previously supported by most of the community. Again, orbital phase-resolved observations are needed.



By the way, our ability to do multi-observatory multi-messenger analyses in the absence of simultaneous observing, hinges on the precision to which data can be lined up in phase space. The goal is to shrink the accumulated phase error across a decade+ to the level of less than 1/10 of an orbital period. This is technically feasible, but thus far has not been attained for many objects. Higher S/N broad-band LCs will improve ephemerides in 2 classes. One small (BH systems with ionizer/scatterer induced modulation), the other very large (X-ray binary pulsars).